

# How Evolved are the Mass Donor Stars in Cataclysmic Variables?

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## 1. Introduction

Cataclysmic variables (CVs) are semi-detached binaries consisting of a white dwarf (WD) primary, a low mass (assumed) main sequence mass donor secondary star ( $M_{don}$ ), and accretion phenomena (stream, disk, etc.). Recent spectroscopic evidence has shown that non-solar metal abundances are present in some CVs. Cheng et al. (1997) determined that the carbon abundance was 5 times solar, nitrogen was 3 times solar, and silicon was  $<0.1$  solar for the white dwarf in WZ Sge. These authors concluded that the most likely source of this non-solar composition material was the mass transferred from the secondary star. Harrison et al. (2000) present IR spectra of three long period systems (U Gem, SS Aur, SS Cyg) and note the apparent weakness of the CO bandheads possibly implying an under abundance of carbon. Long and Gilliland (1999) analyzed the WD spectrum of U Gem and determined that nitrogen was 4 times solar while C was  $<0.1$  solar. The polar BY Cam has been observed in the FUV spectral region and that analysis (Mouchet et al., 2001) has revealed increased nitrogen and decreased carbon abundances in agreement with CNO processing in thermonuclear runaways. Finally, Howell and Ciardi (2001) observed two ultra-short period CVs (LL And and EF Eri) and their IR spectra show very weak CO absorption, indicative of a less than solar carbon abundance.

If we assume that the component stars in a CV are born with either solar composition or if very old, low metal abundance, some mechanism is required to produce the observed anomalies. Nuclear core evolution within the secondary star could possibly provide this mechanism if He burning occurs, that is, if the secondary star reaches an advanced main sequence state or post-main sequence phases in its evolution. Prior to this time, only He enrichment can occur as the core nuclear burning in these low mass stars is via the pp-cycle which does not produce any abundance changes among the CNO elements.

Marks and Sarna (1998) performed a detailed theoretical study of the possible effects

on the surface abundances of the secondary star due to sweeping up common envelope (CE) material or accreting classical nova ejecta; both cases would place thermonuclear processed material onto the secondary star. The work by Marks & Sarna only considered initially massive secondary stars ( $1.0\text{--}1.5\text{ M}_{\odot}$ ) whereas Howell, Nelson, & Rappaport (2001; hereafter HNR) have shown that massive secondaries are likely to represent only a small fraction of all CVs (See §2.2). Recurrent novae, super-soft X-ray sources, and very long period CVs ( $P_{orb} > 7\text{ hr}$ ) are examples of systems with massive and/or evolved secondary stars.

In order to test the possibility that nuclear core evolution might play a role in the chemical anomalies observed, we have undertaken a new population synthesis calculation of over 3 million primordial binaries, of which  $\sim 20,000$  end up as mass transferring CVs. We then statistically examine the age of the mass donors prior to contact to determine what level of core evolution has occurred.

## 2. Secondary Star Evolution

CVs begin as detached binaries containing two main sequence stars which then pass through a common envelope (CE) stage during which the lower mass (secondary) star orbits within the extended outer atmosphere of the faster evolved, more massive star. The core of the more massive or primary star will become the white dwarf that will accompany the low mass star throughout the remainder of its life. CVs which initially contain two low mass components generally require a long time to come into contact after the CE phase. In such systems, the secondary star’s main sequence lifetime is longer than a Hubble time so no significant main sequence core evolution is expected.

If a binary reaches the semi-detached state, ie., mass transfer occurs, at a long orbital period, the masses of the component stars both must be fairly high,  $> 0.4\text{ M}_{\odot}$  (see HNR).

These long period CV's are the systems for which significant core evolution *could* occur in the mass donor prior to contact and within the lifetime of the Galaxy (10 GY). Baraffe & Kolb (2000) examined evolutionary models and showed that for CVs with orbital periods longer than about 7 hr, the secondary stars have initial masses of  $>1M_{\odot}$  and they are evolved prior to contact. These authors used an empirical relation between spectral type and I-K color (derived from stellar models) to obtain a spectral type-orbital period relation for a given mass-effective temperature-luminosity model of the secondary star.

The relation between spectral type and secondary star mass (or  $P_{orb}$ - $M_2$ ,  $P_{orb}$ -Sp. Type) is fairly accurate for CVs with orbital periods below the period gap and for those with  $P_{orb} > 6$  hr (See Warner 1995; HNR). However, for those CVs with periods in the range of 3-6 hr, the secondary star is bloated due to its non-thermal equilibrium state making it larger in radius when compared with a main sequence star of the same mass. The effect is illustrated in Figure 1 through the use of the main sequence (solid line) and proper mass donor (dashed line)  $P_{orb}$ - $M_2$  relationships. Four example secondary stars, in pairs at equal orbital period, are shown in Figure 1. Table 1 provides some theoretical intrinsic properties for the stars in each pair and shows that main sequence values are unreliable to use within the 3-6 hr period range. For example, a CV with  $P_{orb}=3.2$  hr would be estimated to have a mass of  $0.37 M_{\odot}$  while its most likely true mass is only  $0.25 M_{\odot}$ . In addition, using an assumed spectral type for the secondary star based solely on  $P_{orb}$  will also be in error. Thus, the effect of bloating on the stars within the orbital period range of 3-6 hr makes the use of orbital period alone invalid as a pointer to the intrinsic properties of the mass donors.

## 2.1. Secondary Star Evolution After Contact

The evolution for long period CVs ( $P_{orb} > 3$  hr) and the corresponding rapid mass loss of the secondary star, as the orbital period decreases, are illustrated for three example

systems in Figure 2 and Table 2. It can be seen that even an initially massive secondary star ( $\sim 1M_{\odot}$ ) quickly (within 260 million years) becomes a low mass star ( $0.25M_{\odot}$ ). Most secondary stars within long period CVs lose 70% or more of their initial mass within 0.4 GY. Even a casual examination of these well known timescales shows that the mass transfer rate above the period gap is so large that the secondary stars have no chance of nuclear core evolution during their contact phase. Details of the evolution process can be found in HNR.

Thus, if nuclear core evolution within the secondary star does contribute significantly to the non-solar metal abundances observed, it must happen prior to contact (ie., before the start of mass transfer) during the time period in which the secondary evolves essentially as a single main sequence star.

## 2.2. Secondary Star Evolution Prior to Contact

Our population synthesis model starts by choosing a sample of primordial binaries with  $0.8 M_{\odot} < M_1 < 8 M_{\odot}$  and then picking appropriate secondary stars for each based on observational work and stability conditions detailed in HNR. Since the primary star evolves into a white dwarf with a mass that can be as large as  $1.4 M_{\odot}$ , the allowed secondaries can have initial masses of up to  $\sim 1.8 M_{\odot}$ . While HNR’s binary evolution code does not deal with secondaries of initial mass greater than  $1 M_{\odot}$ , an examination of the number of possible systems ignored due to this constraint reveals that it represents only a small fraction of the present day CV population.

Using Monte Carlo techniques, ten new samples of 200,000 initial primordial binaries each were generated for this work. The number of produced binaries which contained secondary stars with initial masses of  $M_2 > 1 M_{\odot}$  was found to be near 0.5% in each set. Thus, of the 3 million primordial binaries used by HNR in their work, the 0.5% value

amounts to having ignored  $\sim 22,000$  systems which started with massive secondaries.

Unless there is some as yet unknown reason why primordial binaries with  $M_2 > 1 M_\odot$  have a greater efficiency for producing mass transferring CVs than their lower mass counterparts, these 22,000 binaries would produce for only 45 present day mass transferring CVs, if they had been properly evolved through their lifetime. This number represents  $\ll 1\%$  of the total HNR sample, all of which would have started mass transfer at  $P_{orb} > 6$  hr.

How does this theoretical result compare with observation? The Ritter & Kolb (1998) catalogue lists 318 CVs which have a known orbital period. Of these, 10% have  $P_{orb} > 6$  hr and probably contain secondary stars of mass greater than  $1 M_\odot$ . Ten of these systems are novae, likely indicating a massive white dwarf which is needed to successfully pair with a massive secondary. Of the six long period systems for which a secondary star spectral type is given, only one is a main sequence star, the rest are post-main sequence objects. Thus, we find strong evidence that very long period CVs contain evolved secondaries of mass  $> 1 M_\odot$ , a result in agreement with Baraffe & Kolb (2000). Of the  $\sim 1000$  CVs known at present, those with long orbital periods are brighter and highly favored for observational discovery. Taken at face value, one would infer that the 30 or so CVs known in Ritter & Kolb with massive secondaries represent 3% of the total present day population of 1000. However, the extreme observational bias present for discovery of long period, bright CVs compared with the vast majority of fainter, shorter period systems. Figure 9 in HNR shows that CVs with  $P_{orb} > 6$  hr are  $\sim 1000$  times more likely to be discovered than those with  $P_{orb} < 6$  hr, making the observed 3% actually represent  $\ll 1\%$  of the true population. This small predicted value is in quite good agreement with the theoretical result given above based on our population synthesis selection of primordial binaries and their subsequent evolution. Given that the vast majority of CVs start their lives with orbital periods of  $< 6$  hr and secondary stars with initial masses of  $< 1 M_\odot$ , we now examine the likelihood of nuclear core evolution in the secondary stars of these, the majority of CVs.

We present in Figure 3 the percent of the main sequence lifetime reached prior to contact for each secondary star in our model population for those binaries which were successful at becoming mass transferring CVs within the lifetime of the Galaxy. Figure 3 contains about 20,000 systems and is based on the theoretical work presented in HNR. We see that most secondary stars come into contact early in their main sequence life, generally within about 5-10% of their ZAMS time. Less than 5% of all donors evolve beyond one-fifth of their main sequence lifetime prior to Roche Lobe contact. The peak in the distribution seen near  $0.7 M_{\odot}$  is due to the trade off between earlier contact time for more massive (larger) secondary stars (these must be paired with a massive WD), and the much longer main sequence lifetimes for secondaries initially of mass  $< 0.7 M_{\odot}$ . A CV which comes into contact with a  $0.7 M_{\odot}$  secondary typically does so at an orbital period near 5.0-5.5 hr. Figure 3 illustrates that even massive secondaries are unlikely to advance past 20% of their main sequence lifetime prior to contact.

### 3. Conclusion

From the results presented in §2.2 it is unlikely that nuclear core evolution (ie., He burning) *prior* to contact can be an important component leading to non-solar metal abundances within the atmospheres of the vast majority of present day secondary stars in CVs. Additionally, the rapidity of the secondary star evolution to very low mass after contact can produce no core evolution of any kind beyond that already determined for the star prior to contact. Thus, we are forced to conclude that no significant nuclear core evolution, specifically CNO abundance changes, will occur for the vast majority of the secondary stars in the present day population of CVs. Therefore, any observed atmospheric abundance anomalies must be attributed to either material swept up by the secondary star during CE evolution or material accreted by the secondary star during classical novae

eruptions on the white dwarf. Primordial abundances could also be considered, however, even for CVs of advanced age this seems to only allow for lower metal abundances not enhanced values as have been observed.

Marks and Sarna (1998) and Sarna et al. (1995) have modeled the CNO burning processes of both CE and nova thermonuclear reactions. They find that if the secondary star accretes  $\sim 0.05 M_{\odot}$  of material during the CE phase, its  $^{12}\text{C}/^{13}\text{C}$  and  $^{16}\text{O}/^{17}\text{O}$  ratios would fall to near half the solar value. Livio & Truran (1994) and Kovetz & Prialnik (1997) also modeled turbulent nuclear burning and CNO redistribution via nova processes. All of these authors generally agree that an enhancement of nitrogen, stationary or decreased oxygen, and depletion of carbon are the by-products of the CNO nuclear processes made available to the secondary star during the CE stage or following the dredge-up of matter from an underlying CO core during a classical nova outburst. The non-solar CNO abundances observed in CVs appear to agree with the trends outlined in these theoretical calculations.

Determinations of accurate CV metallicities will require high S/N (50-100) continuum spectroscopic observations. For example, even at 2.2 microns the secondary star is often not the dominate flux source. Any spectroscopic observations aimed at abundance determinations must realistically account for rapid rotation effects and accretion flux contributions, both of which distort spectral lines, in order to properly measure absorption features. Given that low mass, He core white dwarfs are unlikely to produce nova outbursts, spectroscopic identification of non-solar abundances (consistent with nuclear by-products) in such a CV would provide strong evidence in favor of significant pollution of the secondary star composition during the CE phase.

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## 4. References

- Baraffe, I., & Kolb, U., 2000, MNRAS, 318, 354.
- Beuermann, K., Baraffe, I., Kolb, U., & Weichhold, M., 1998, A&A, 339, 518.
- Cheng, F., Sion, E., Szkody, P., & Haung, M., 1997, ApJ, 484, L149.
- Cox, A., 2000, “Astrophysical Quantities”, AIP press, Chps. 7 & 15.
- Harrison, T., McNamara, B., Szkody, P., & Gilliland, R., 2000, AJ, 120, 2649.
- Howell, S. B., Nelson, L., & Rappaport, S, 2001, ApJ, 550, 897. [HNR]
- Howell, S. B., & Ciardi, D., 2001, ApJL, 550, L57.
- Kovetz, A., & Prialnik, D., 1997, ApJ, 477, 356.
- Livio, M., & Truran, J., 1994, ApJ, 425, 797.
- Long, K., & Gilliland, R., 1999, ApJ, 511, 916.
- Marks, P., & Sarna, M., 1998, MNRAS, 301, 699.
- Miller, G., & Scalo, J., 1979, ApJS, 41, 513.
- Mouchet, M., Bonnet-Bidaud, J.-M., Beuermann, K., De Martino, D., Ferlet, R., Fried, R., Howell, S. B., Lecaveleir Des Etangs, A., Mukai, K., Porquet, E., Roueff, E., & Szkody, P., 2001, “Cosmic Evolution”, World Scientific, in press.
- Ritter, H., & Kolb, U., 1998, A&AS, 129, 83.
- Sarna, M., Dhillon, V., Marsh, T., & Marks, P., 1995, MNRAS, 272, L41.
- Smith, D., & Dhillon, V., 1998, MNRAS, 301, 767.

Table 1. Model Stars in Figure 1<sup>a</sup>

Parameter	Model A	Model B	Model C	Model D
Mass ( $M_{\odot}$ )	0.37	0.25	0.47	0.37
Radius ( $M_{\odot}$ )	0.38	0.32	0.46	0.42
$P_{orb}$ (hr)	3.2	3.2	4.0	4.0
$\log g$	4.84	4.82	4.78	4.76
$T_{eff}$ (K)	3300	3600	3700	3800
Sp. Type(1) <sup>b</sup>	M5.2	M5.2	M3.2	M3.2
Sp. Type(2) <sup>c</sup>	M3	M2	M0.5	M0
B-V(1) <sup>d</sup>	1.62	1.62	1.55	1.55
B-V(2) <sup>d</sup>	1.58	1.49	1.45	1.4
I-K(1) <sup>e</sup>	2.5	2.5	2.3	2.3
I-K(2) <sup>e</sup>	2.2	2.0	1.71	1.65

<sup>a</sup>Models are calculated based on the work presented in HNR.

<sup>b</sup>From Smith & Dhillon (1998) relation of spectral type vs.  $P_{orb}$ .

<sup>c</sup>Based on MK Spectral Classification assuming main sequence stars with the given  $T_{eff}$  (Cox 2000).

<sup>d</sup>Based on  $T_{eff}$  and spectral type for main sequence stars (Cox 2000).

<sup>e</sup>Based on spectral type, from Beuermann et al., (1998).

Table 2. Time (GY) Since Initial Contact for the Three  
Models Shown in Figure 2

Number in Fig. 2	$M_1=1.4M_\odot$ $M_{don}=1.0M_\odot$	$M_1=0.6M_\odot$ $M_{don}=0.5M_\odot$	$M_1=0.3M_\odot$ $M_{don}=0.2M_\odot$
1	0.01	0.02	0.6
2	0.07	0.09	2.3
3	0.13	1.8	3.9
4	0.27	4.2	5.5
5	0.90	5.5	–
6	1.7	9.7	–
7	2.8	–	–
8	3.5	–	–
9	4.6	–	–

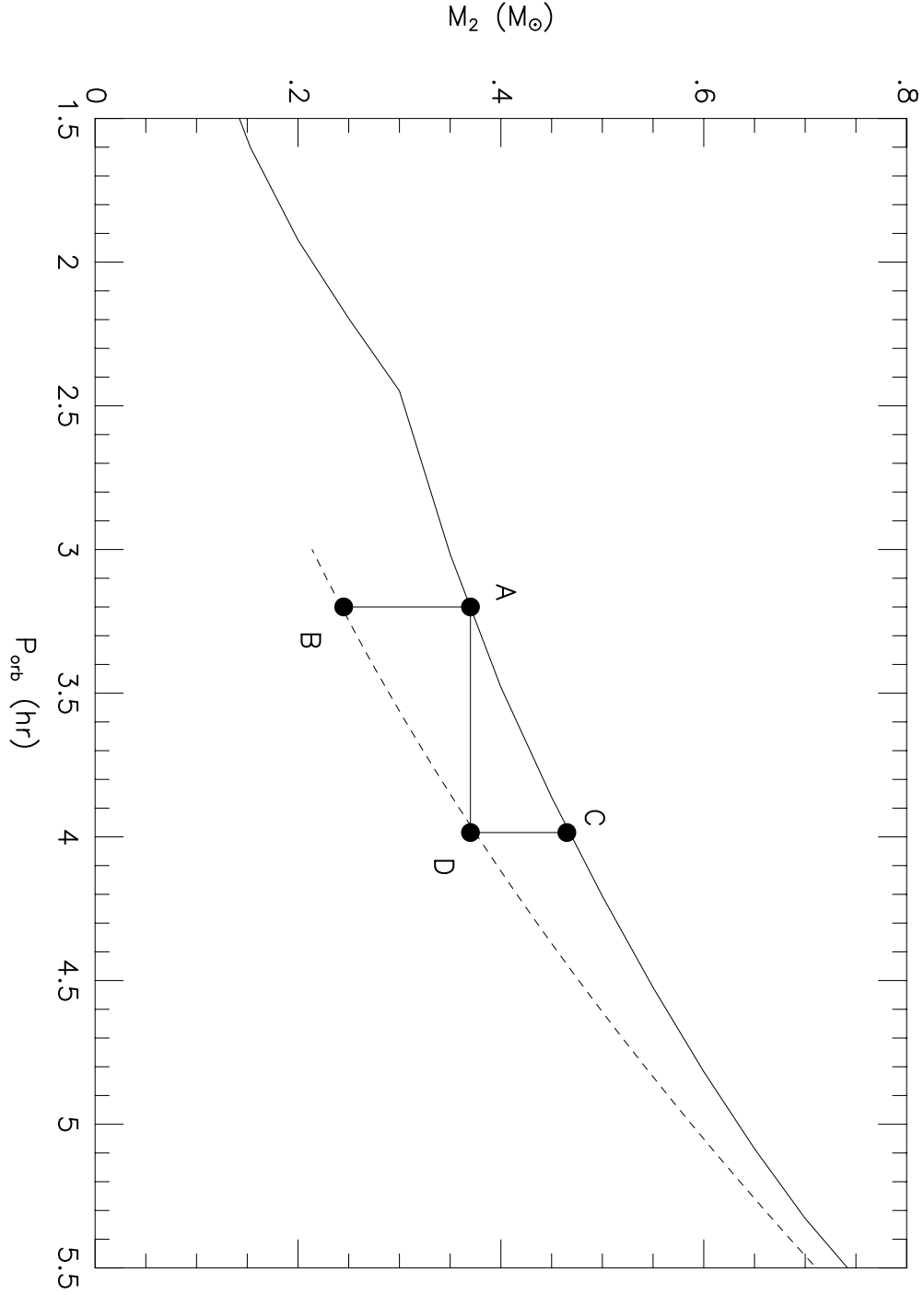


Fig. 1.— An illustration of the effect of bloating on the secondary stars in CVs. The solid line is the main sequence relation and the dashed line is that for mass transferring secondaries in CVs. Below the period gap and above 6 hr, the two relations are essentially the same. The four model secondaries have their parameters listed in Table 2. Bloating is most extreme between orbital periods of 3-5 hr.

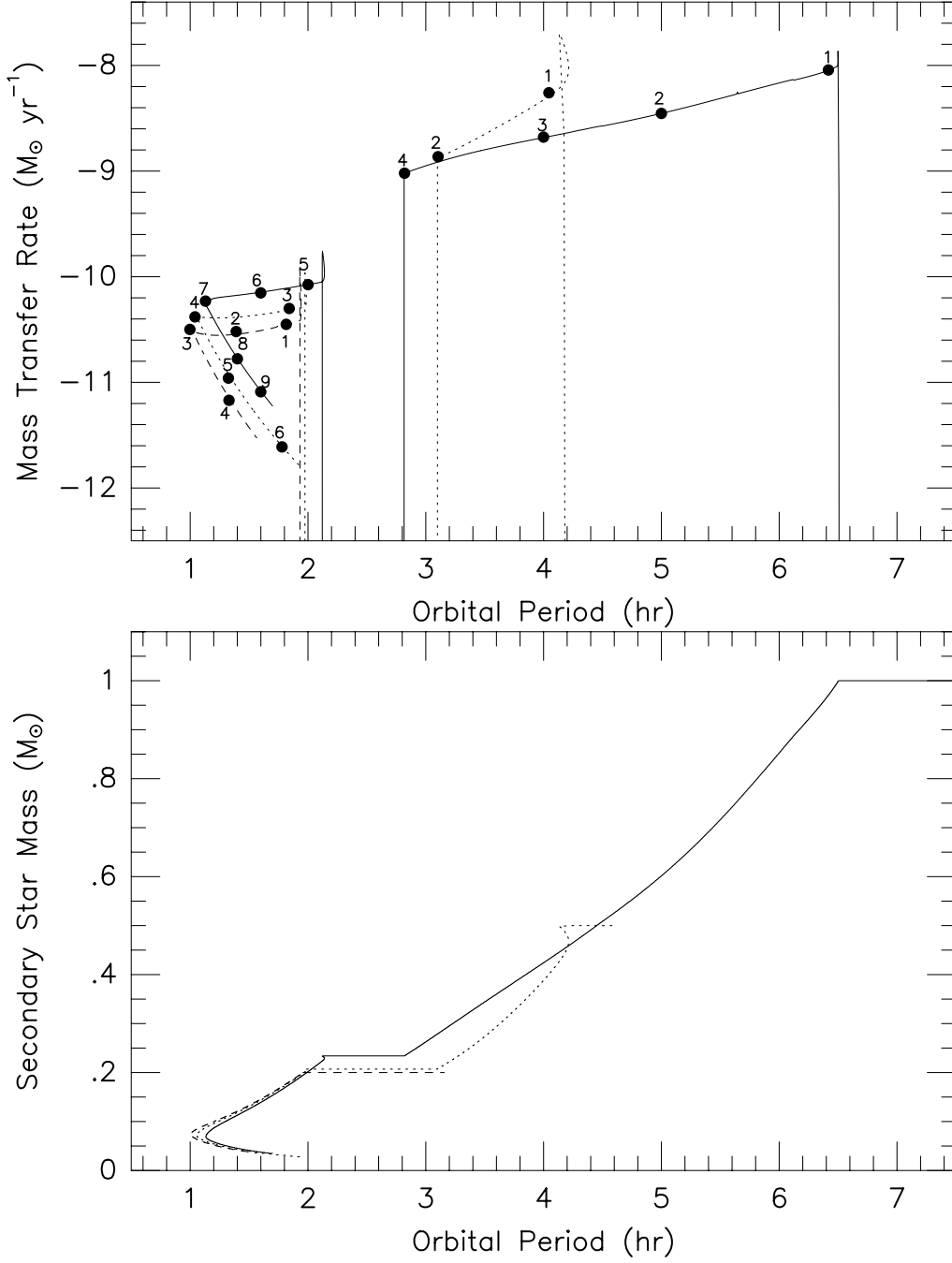


Fig. 2.— The top panel presents three representative CV evolutions in the orbital period, mass transfer plane. The three models are (solid) a CV with  $M_1 = 1.4 M_{\odot}$  and (initially)  $M_{don} = 1.0 M_{\odot}$ , (dotted) a CV with  $M_1 = 0.6 M_{\odot}$  and  $M_{don} = 0.5 M_{\odot}$ , and (dashed) a CV with  $M_1 = 0.3 M_{\odot}$  and  $M_{don} = 0.2 M_{\odot}$ . The numbers refer to a time history for each model as listed in Table 2. The bottom panel shows the same three models but in the orbital period, secondary

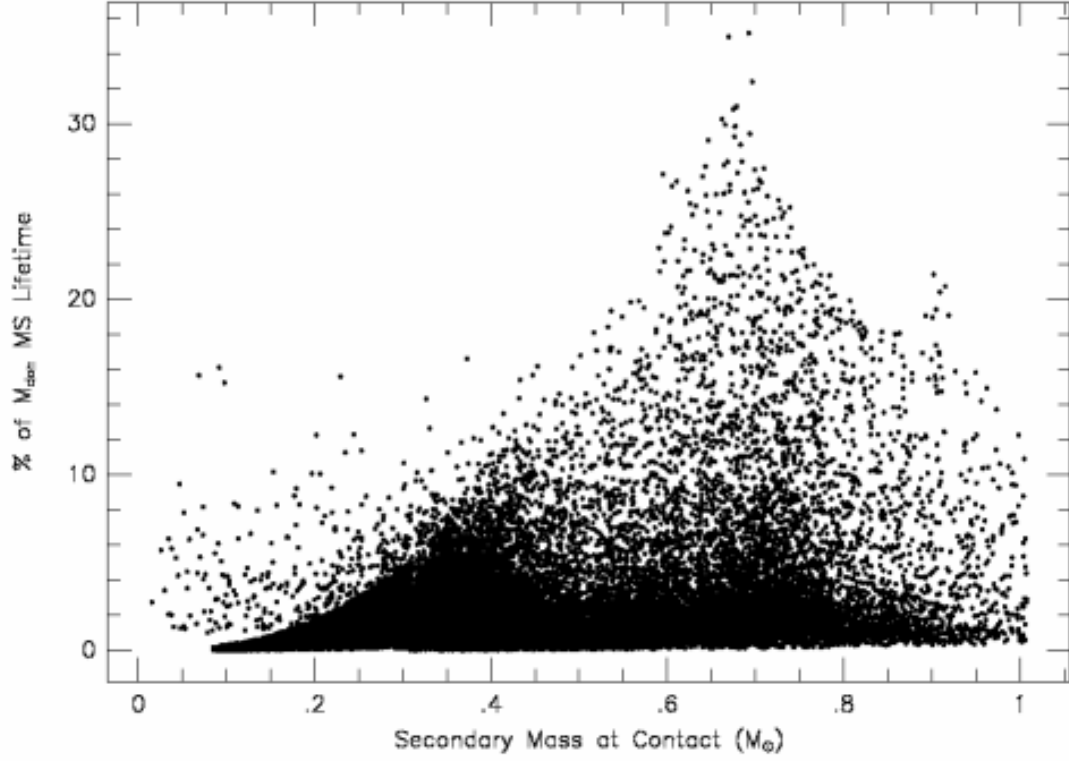


Fig. 3.— The percent of the secondary star main sequence lifetime which has passed prior to the beginning of mass transfer vs. the secondary star mass at the time of initial contact. Most secondary stars have initial Roche lobe contact early in their main sequence lives. See text for details.